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Channelling of 2.4 GeV Ar ions in a germanium crystal (*)

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Résumé. — Nous présentons la première étude expérimentale de canalisation d'ions lourds de très haute énergie. Réalisée avec des ions d'argon de 60 MeV par nucléon et un cristal de germanium d'épaisseur 100 μm, cette étude avait pour but principal de déterminer les conditions expérimentales et les techniques adaptées à l'observation de la canalisation de tels projectiles. Nous montrons que la détection des gammas, des neutrons et des produits de fragmentation du faisceau émis vers l'avant permet d'orienter un cristal mince et de mesurer les paramètres de la canalisation, χ_{min} et $\psi_{1/2}$, que nous avons trouvés en accord raisonnable avec les estimations théoriques.

Abstract. — We present the first experimental channelling study with very energetic heavy ions. This work, performed with 60 MeV/u argon projectiles bombarding a 100 μm thick germanium crystal, aimed at determining the experimental conditions and techniques suitable to the observation of channelling effects with such projectiles. We show that the detection of forward emitted gamma-rays, neutrons and beam fragmentation products allows us to get the crystal aligned and to measure the channelling parameters, χ_{min} and $\psi_{1/2}$, which we find to be in reasonable agreement with theoretical estimates.

1. Introduction.

The discovery of fast charged particle channelling in crystal targets, a little more than 20 years ago, gave rise to a number of experiments involving incident projectiles either positively charged (ions and particles) or negatively charged (hadrons and leptons), at incident energies ranging from keV to GeV [1]. Most of the channelling effects can be analysed in the frame of classical models where atomic planes and rows are described as continuous repulsive or attractive entities for positive and negative projectiles respectively. These models correctly predict, at relativistic and non-relativistic velocities, the channelled trajectories, the critical angles and the yield of small impact parameter interactions between the projectile and the crystal atoms, except for light projectiles, such as electrons, for which the classical model breaks down. Individual channelling states must then be studied by using relativistic quantum mechanics.

Up to now positive ion channeling experiments have been performed mainly at low velocity (energies ~ MeV/u) in transmission or backscattering geometries, and at high velocity with GeV protons. Channeling of medium velocity heavy ions has been studied only in two experiments, one using 80 MeV I and Br ions [2], and the other using ~ 100 MeV uranium fission fragments [3]. We describe hereunder the first channelling experiment (to our knowledge) of high energy heavy ions. We used a beam of 2.4 GeV Ar ions and a Ge crystal target. At such an energy the incident projectile largely overcomes the Coulomb barrier of the target nuclei; then various inelastic nuclear processes can occur, the most probable being the fragmentation of the projectile nucleus. The aim of this work was to find the easiest and cleanest way of observing channelling effects for high energy heavy

(*) Experiment performed at the French National Laboratory G.A.N.I.L.

ions. For that we measured the crystal orientation dependence of various nuclear reaction yields by detecting particles and radiations emerging from the crystal target.

The experiment was performed on the LISE [1] beam line of the GANIL [2] heavy ion accelerator in Caen. The results compare very satisfactorily with theoretical predictions for the values of minimum yields and critical angles.

2. The experiment.

We used a thin crystal target, for the following reasons: i) dechannelling effects are small, ii) forward emitted particles can be detected downstream from the crystal, iii) the intensity of the ion beam transmitted through the target can be measured and used to normalize the data.

Critical angles ψ_c for channeling of GeV heavy ions are very small, typically a fraction of milliradian. The determination of channelling critical angles and minimum yields from the measurement of nuclear reaction yields requires severe conditions on the flatness of the thin crystal target and also on the angular divergence of the incident beam. The needed angular divergence must be an order of magnitude smaller than ψ_c. Such a requirement was possible on the LISE beam line at GANIL, a line especially designed to deliver beams of excellent definition in space and energy. The optics of the beam line was calculated so as to give an angular divergence of the order of 10^{-4} radian, and the results of the present experiment show that this objective has been attained [4]. The beam spot diameter was 0.6 cm on the target, and the mean intensity was 2.5 nA of Ar^{16+}, i.e. $\sim 10^9$ pps. The duty cycle of the incident beam (microstructure : 1 ns/100 ns; macrostructure : 1 ms/2 ms) did not cause major pile-up problems in the detectors and associated electronics.

The target used in this experiment was a (111) Ge single crystal plate. The crystal was mounted on a 3-axis goniometer, working in the transmission mode, moving by steps of 10^{-2} degree. The target thickness was 100 μm; then the energy lost by the projectiles when the crystal was not aligned was about 120 MeV, a too small value to heat significantly the target. In fact we measured that the crystal temperature never exceeded 2° above room temperature during irradiation. On the other hand the crystal plate was thick enough to remain satisfactorily flat when mounted on the goniometer. X-ray measurements showed that the overall curvature of the 1 cm² crystal plate was less than 0.1 mrad when the crystal was fixed on the target holder by a unique drop of wax. A channelling measurement was also made with 2 MeV α particles in order to control the crystal quality and to prealign the target in the goniometer.

Various radiations and particles emerging from the crystal target could be used to reveal channelling effects. In the present experiment large cross section nuclear processes lead to γ-ray emission and to the forward emission of light particles (including neutrons) and of fragments of the incident projectile. Unfortunately the emission of high energy particles and γ-rays gives an information on channelling that is integrated over the full pathlength of the projectile in the crystal.

The experimental set up is shown in figure 1. The incident Ar^{16+} beam is optically prepared in the LISE beam line, and sent through the goniometer (G) that holds the Ge crystal. The fragmentation products are detected at 6° by a 300 μm Si surface barrier detector (SBD). Fast light particles are detected by a NE 213 liquid scintillator detector (LS) located at 10°, out of the target chamber. At this angle the light particles are mainly protons and neutrons of velocities close to the beam velocity. Since the particles have to penetrate a few cms of aluminum before reaching LS, only the neutrons will reach this detector. A pulse shape discriminator was used to separate neutrons from γ-rays.

The transmitted beam was collected in a Faraday Cup (FC) located in a beam blocker (BB). Since the Faraday Cup current was too small to monitor the beam intensity we installed a neutron detector (N) between the beam blocker and an albedo blocking wall (AB). This detector counted neutrons produced by the beam in and around the cup, with a counting rate approximatively proportional to the beam intensity, and was then used to monitor the experiment.

3. Results and discussion.

In figure 2 we show the angular dependence of the yield of the fragmentation products. Narrow dips are observed along $(1\bar{1}0)$, $(2\bar{1}\bar{1})$ and $(10\bar{1})$ planar directions. In figure 3 we show a scan of the same yield across the [111] axis. In figure 4 we show an

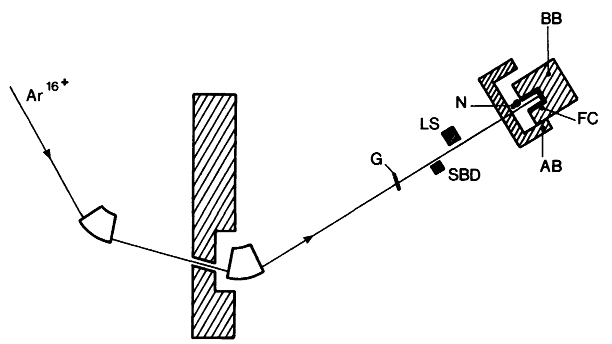

Fig. 1. — Experimental set-up, G : goniometer, SBD : fragment detector, LS neutron detector, N : neutron detector used as a monitor, FC : Faraday cup, BB : beam blocker, AB : albedo blocking.

([1]) LISE : Ligne d'Ions Super Epluchés (Highly Stripped Ion Beam Line).

([2]) GANIL : Grand Accélérateur National d'Ions Lourds.

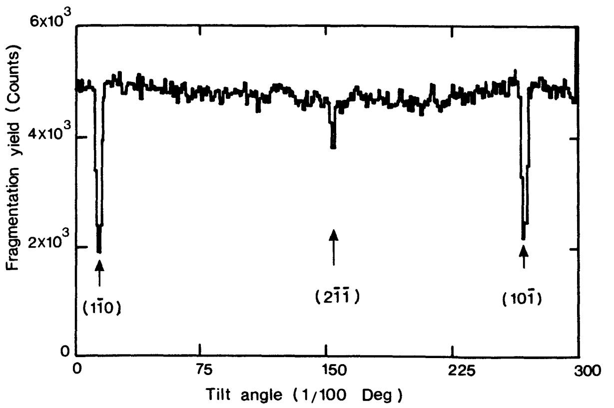

Fig. 2. — Angular scan of the fragmentation product yield around the [111] axis of the Ge crystal. Raw data showing planar channelling in two { 110 } and one { 211 } planar directions. The beam dose is $\sim 10^{10}$ ions per channel, and the angular step 0.01° per channel.

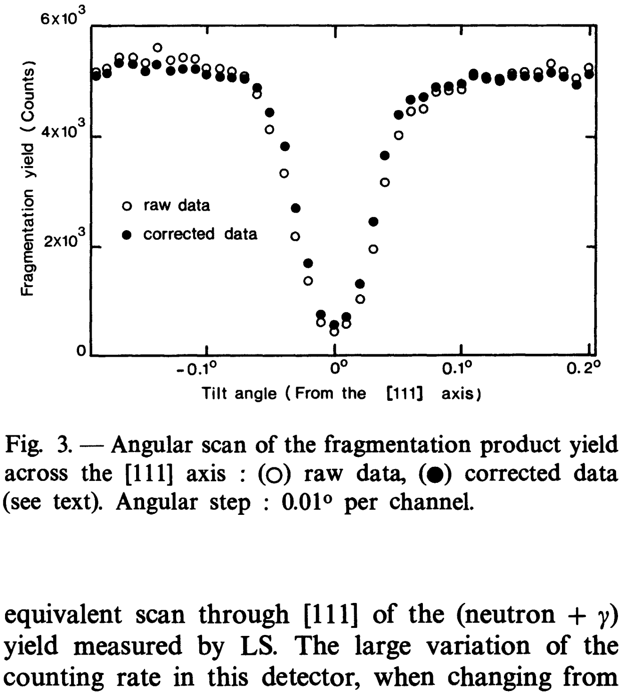

Fig. 3. — Angular scan of the fragmentation product yield across the [111] axis : (○) raw data, (●) corrected data (see text). Angular step : 0.01° per channel.

equivalent scan through [111] of the (neutron + γ) yield measured by LS. The large variation of the counting rate in this detector, when changing from random to aligned conditions, made difficult a perfect neutron-γ discrimination. These three scans demonstrate that channelling effects are clearly observable with energetic heavy ions. Since the scans in figures 3 and 4 are nearly identical (minimum yield χ_{min} and half angular width $\psi_{1/2}$ of the dips) we conclude that both types of detection are convenient for measuring channelling properties and that neutron and γ-ray backgrounds are very low in the target room. The structures which help reducing the radiation background are the thick wall located up-stream from the last magnet of the LISE spectrometer and the well shielded beam-blocker at the end of the line (Fig. 1). When the crystal is removed, the ion beam goes through the hole of the target holder (diameter 1.8 cm) and one gets no fragment, no γ-ray

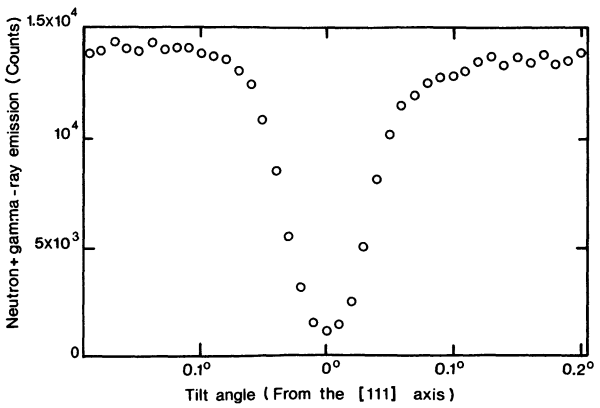

Fig. 4. — The same scan (raw data) as in figure 3 for the (neutron + γ-ray) emission.

and about 20 neutrons for an ion dose corresponding to each measurement of the scans of figures 3 and 4. This is another confirmation that the background is very low at the site of the detectors.

We noticed that the counting rate in the monitor was not strictly independent of the crystal orientation : the time duration needed to reach a given number of neutrons in the monitor (N) showed a systematic dependence upon the tilt angle of the crystal relative to axial or planar directions, which was superposed on the fluctuations resulting from the variation of the beam intensity. The reason for this is that the number of neutrons reaching (N) depends slightly upon the beam size in the cup (FC), and that the angular spread of the transmitted beam is reduced in channelling conditions, in such a way that the neutron yield in (N) is slightly increased. By recording the mean accumulation time at each orientation for planar and axial scans we were able to correct this defect of the monitor, since the effective beam dose happens to decrease linearly with the yield χ. A typical corrected scan is shown on figure 3, together with raw data.

Raw and corrected values of $\psi_{1/2}$ and χ_{min} which are given in table I for [111] and (110) directions have been obtained from the fragmentation product measurements.

We compared these experimental results with Monte Carlo simulations [5, 6]. The calculations of reference [5] give the values of χ_{min} for axial channelling and the values of $\psi_{1/2}$ for axial and planar channelling, for small penetration depths into the crystal, and for a given inter-atomic potential. Generally one uses the Molière approximation of the Thomas Fermi screening function. However, in our case the choice of an adequate screening length is not obvious. For a stripped light ion, inducing only a small perturbation, the Thomas Fermi screening radius $a_{TF} = 0.8853\, a_0\, Z_2^{-1/3}$ is well adapted [7]. In our experiment most of the ions are fully stripped but they have a high Z and probably perturb the electronic environment of the target atoms during the collision.

Table I. — *Experimental and theoretical values of* $\psi_{1/2}$ *and* $\chi_{\min}$. *Comparison (col. 7-8) between experiment (col. 2) and theory (col. 5-6). Experiment (fragmentation yields measurements) : raw data (col. 1) and corrected for the monitoring (col. 2). Theory : columns* TF *and* L *correspond to the fully stripped ion approximation* (a_{TF}) *and the neutral atoms approximation* (a_L), *respectively (see text); thin crystal approximation (col. 3-4), and with dechannelling included (col. 5-6). Note that the measurement along the* (110) *plane is compared with theoretical* $\psi_{1/2}$ *values that do not include dechannelling effects.*

		EXP		THEORY				EXP_{corr}/TH_{dechan}	
				Surface		Dechan.			
		1	2	3	4	5	6	7	8
		raw	corr.	T.F.	L.	T.F.	L.	T.F.	L.
< 111 > axis	$\psi_{1/2}$ (mrad)	0.64	0.57	0.92	0.83	0.74	0.66	0.77	0.86
	$\chi_{\min}$	0.07	0.10	0.031	0.033	0.065	0.067	1.54	1.49
$\{110\}$ plane	$\psi_{1/2}$ (mrad)	0.25	0.25	0.36	0.32			0.70	0.79
	$\chi_{\min}$	0.38	0.50	0.14	0.14	0.33	0.33	1.50	1.50

Then, the screening length is expected to lie between the Thomas Fermi value and the value proposed by Lindhard, which corresponds to the collision between two nearly neutral atoms, $a_L = 0.8853\, a_0(Z_1^{2/3} + Z_2^{2/3})^{-1/2}$, where a_0 is the Bohr radius and Z_1 and Z_2 are the atomic numbers of the projectile and target atoms respectively.

Here the velocity of the incident projectiles is such that a relativistic correction must be done for the calculation of the critical angles. ψ_c is proportional to $\left(E\dfrac{\gamma+1}{2\gamma}\right)^{-1/2}$ where E is the kinetic energy of the projectiles and γ the relativistic factor. Here, $\gamma = 1.06$, and the small correction (+ 1.5 %) is included in the predictions for $\psi_{1/2}$ that are given along with those for $\chi_{\min}$ in table I, for the two values of the screening length.

In order to compare our results with the theory, dechanneling must also be evaluated. One could expect from theoretical estimates that the dechannelling effects in major axial and planar directions are weak in our experiment. Indeed we observed this, when we performed two measurements of $\chi_{\min}$ along (110), with two different particle pathlengths obtained by tilting the target : when the pathlength increases by 25 %, the value of $\chi_{\min}$ increases only from 0.38 to 0.44.

Dechanneling in thin targets affects mainly the particles entering the crystal with a large transverse energy for which elastic nuclear scattering dominates. In this case a reduced depth $\underset{\sim}{x}$ for axial channelling can be deduced [8].

$$\underset{\sim}{x} \propto \psi_v^2/\psi_c^2 \propto \frac{Z_1\, Z_2\, d u_1^2\, x}{E}$$

where ψ_c is the Lindhard critical angle, ψ_v the width of the multiple scattering angular distribution, d the interatomic distance in the row, u_1 the r.m.s. thermal vibration amplitude in one direction, E the incident energy and x the penetration depth. With this scaling factor one can extrapolate dechannelling results obtained in the MeV energy range [7] and correctly incorporate the dechannelling effect in the calculation of $\psi_{1/2}$ and $\chi_{\min}$ in the axial case.

In the case of planar channeling the Monte Carlo simulation in reference [6] gives a prediction of the dechanneling effect on $\chi_{\min}$. We used the results obtained for low energy ^{4}He projectiles in (110) Ge, and we simply scaled the results by a factor $Z_1\, x/E$ to predict the planar dechannelling effect on $\chi_{\min}$, since here dechanneling is mainly due to nuclear scattering. Unfortunately there is no simple way, in the planar case, to calculate $\psi_{1/2}$ when dechannelling is not negligible.

All the calculated values taking dechannelling effects into account, except for the planar critical angles, are shown in table I.

The comparison of our experimental results with the theoretical predictions (Table I), shows that, on the average, the ratio of the experimental (corrected) value of $\psi_{1/2}$ on the theoretical value is $\psi_{1/2}^{\exp}/\psi_{1/2}^{\text{th}} \sim 0.78$. This ratio is only slightly smaller than the ratios generally observed at MeV energies. This indicates, as expected, that the Lindhard scaling laws for critical angles are still valid in the energy domain considered here. However the same comparison applied to the minimum yields reveals a perhaps more significant discrepancy since the ratio $\chi_{\min}^{\exp}/\chi_{\min}^{\text{th}}$ is about 1.5.

It should be noticed that the measured value of $\chi_{\min}$ along { 110 } was the same at the beginning and at the end of the experiment. That means that, for the typical ion dose used in this experiment, there is no observable radiation damage induced in the crystal by the incident projectiles.

From the discrepancy on the $\chi_{\min}$ values we tried to extract informations about the combined effect of beam divergence and crystal curvature and defects over the large beam spot on the target. We have assumed that these factors combine to give a Gaussian angular distribution of the beam, characterized by a standard deviation σ_φ. Calculations performed with this simplifying assumption show that $\chi_{\min}$ is much more affected than $\psi_{1/2}$. Assuming a parabolic shape for the lower part of the angular scans, the comparison of experimental and calculated $\chi_{\min}$ values gives σ_φ. We find, both for planes and axes : $\sigma_\varphi = 0.15 \pm 0.05$ mrad. However one cannot determine which of beam angular divergence, crystal curvature and crystal defects dominates in σ_φ.

4. Conclusion.

The high quality of the optics of the ion beam and the low level of the radiation background in the target room have allowed to observe channelling properties of GeV Ar ions in a thin crystal. The results compare very satisfactorily with theoretical predictions.

We have also shown that radiation damage effects in the crystal target should not be a major problem for the future development of channelling experiments with very energetic heavy ions.

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